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## Reaction times of manual responses to a visual stimulus at the goal of a planned memory-guided saccade in the monkey

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**Abstract** Monkeys demonstrate improved contrast sensitivity at the goal of a planned memory-guided saccade (Science 299:81–86, 2003). Such perceptual improvements have been ascribed to an endogenous attentional advantage induced by the saccade plan. Speeded reaction times have also been used as evidence for attention. We therefore asked whether the attentional advantage at the goal of a planned memory-guided saccade led to speeded manual reaction times following probes presented at the saccade goal in a simple detection task. We found that monkeys showed slower manual reaction times when the probe appeared at the memorized goal of the planned saccade when compared to manual reaction times following a probe that appeared opposite the saccade goal. Flashing a distractor at the saccade goal after target presentation appeared to slow reaction times further. Our data, combined with prior results, suggest that a spatially localized inhibition operates on the neural representation of the saccade goal. This inhibition may be closely related or identical to the processes underlying inhibition-of-return. We also found that if the same detection task was interleaved with a difficult perceptual discrimination task, manual reaction times became faster when the probe was at the saccade goal.

We interpret these results as being an effect of task difficulty; the more difficult interleaved task may have engaged endogenous attentional resources more effectively, allowing it to override the inhibition at the saccade goal. We construct and discuss a simple working hypothesis for the relationship between the effects of prior attention on neural activity in salience maps and on performance in detection and discrimination tasks.

**Keywords** Attention · Saccades · Reaction time · *Macaca Mulatta*

### Introduction

Attention, measured as an improvement of perceptual discrimination performance, shifts to the goal of a saccade just before the saccade is executed (Hoffman and Subramaniam 1995; Kowler et al. 1995; Deubel and Schneider 1996; Deubel and Schneider 2003). Recently, Bisley and Goldberg (2003) extended this observation to the delay period of a memory-guided saccade. They demonstrated that monkeys showed improved contrast-sensitivity at the saccade goal while they were waiting to make a planned memory-guided saccade. They ascribed this improvement in contrast-sensitivity to an attentional advantage induced by the saccade plan. Their data provided, for the first time, direct evidence for a linkage between sustained covert attention and sustained oculomotor preparation. Such evidence is crucial for theories that posit that covert visuospatial attention is identical to oculomotor preparation and that the presence of one implies the other (Klein and Pontefract 1994; Rizzolatti et al. 1994). According to these theories, covertly attending to a location should result in facilitated saccades toward that location and similarly, preparing a saccade toward a location should be accompanied by covert attentional allocation to the saccade goal (Klein and Pontefract 1994).

Similar results have recently been obtained in human subjects: performance accuracy on a delayed

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identification task was shown to be higher at locations that had been marked as potential saccade goals (Van der Stigchel and Theeuwes 2005). However, behavioral results from manual reaction time tasks have yielded seemingly contradictory results, despite the fact that speeded manual reaction times following a probe are also often used as evidence for prior attentional allocation to the location of the probe. At least two studies in humans have failed to show an attentional advantage at the goal of an intended saccade using manual reaction time as the behavioral measure (Klein and Pontefract 1994; Ostendorf et al. 2004), despite the evidence for attentional allocation to the saccade goal obtained using accuracy measures from discrimination tasks. However, the apparent contradiction rests on a comparison of results derived from studies using very different tasks. We therefore set out to explore this issue more thoroughly by measuring manual reaction times to a probe presented at the goal of a planned saccade in a task similar to the one in which attentional allocation had previously been demonstrated at the saccade goal (Bisley and Goldberg 2003).

It is well known that the sudden onset of a flashed stimulus draws attention toward the stimulus location resulting in enhanced perceptual sensitivity (Pestilli and Carrasco 2005) and faster reaction times (Posner et al. 1985). It has also been shown that such a flash can transiently draw attention away from the goal of a memory guided saccade, as measured by enhanced perceptual sensitivity at the distractor location (Bisley and Goldberg 2003). Because reaction times and accuracy measures could potentially index different stages of sensorimotor processing, our second aim was to see if the transient shift of attention induced by a flashed distractor led to faster reaction times to probes presented at the distractor location in a similar manual reaction time task.

Some of these results were previously presented in abstract form (Sirotin et al. 2004).

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## Methods

### Subjects

All experimental protocols were approved by the Animal Care and Use Committees at Columbia University and the New York State Psychiatric Institute as complying with the guidelines established in the Public Health Service Guide for the Care and Use of Laboratory Animals. Two male rhesus monkeys (*Macaca mulatta*) weighing approximately 9 kg each had scleral search coils to monitor eye position (Judge et al. 1980) and head restraining devices implanted during sterile surgery under ketamine and isoflurane anesthesia. Monkey I also had a recording chamber implanted on the skull over the left parietal cortex and had previously learned a go/no-go memory-guided saccade task (described below, also see Bisley and Goldberg 2003).

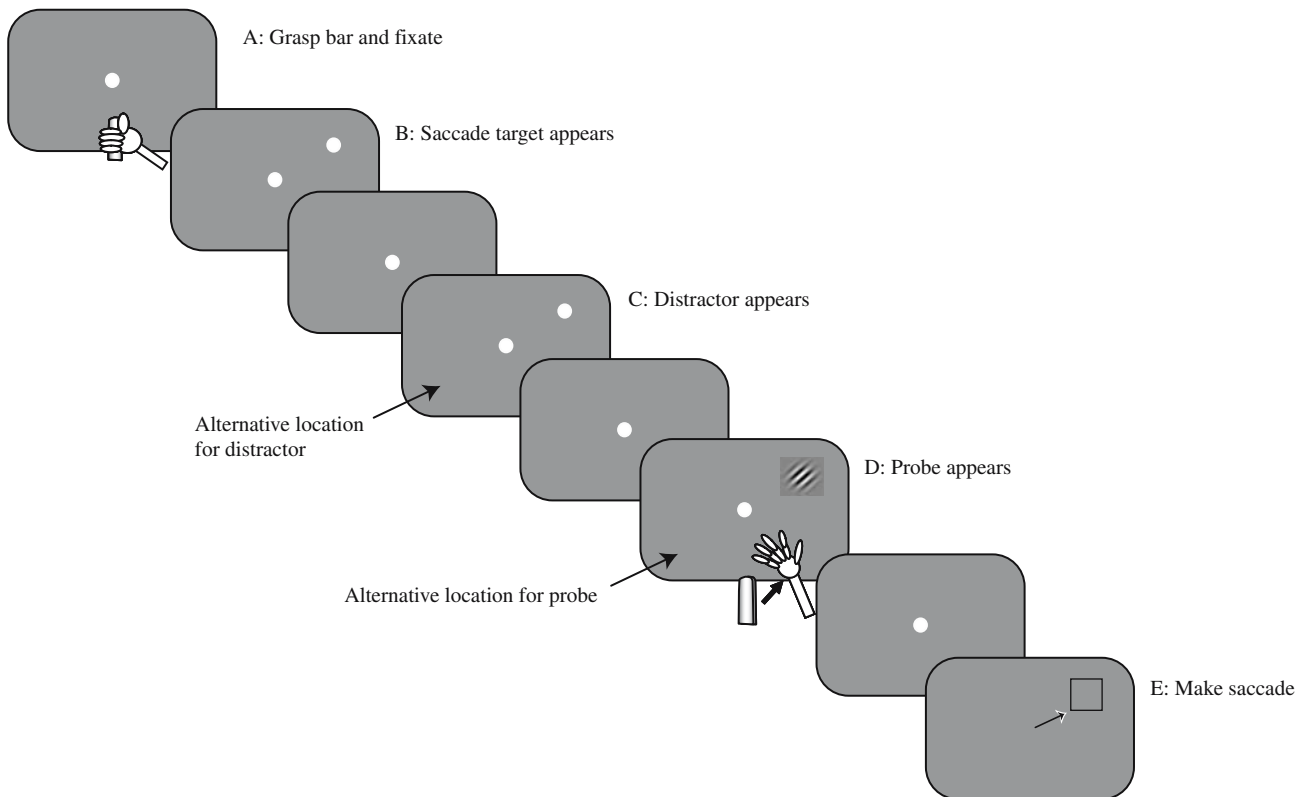
### Behavioral tasks

Behavioral control and data collection (eye-position traces, stimulus events, and bar-release times) were performed on a Dell Optiplex computer using the REX system (Hays et al. 1982) running on the QNX operating system. Visual stimuli were back-projected on a tangent screen by a Hitachi CP-X275 LCD projector under the control of a Dell Dimension PC running the GLVEX graphics system. The background luminance was 50 cd/m<sup>2</sup> (measured with a Minolta LS-110 Luminance Meter) and the projector refresh rate was 60 Hz. Stimulus timing was calculated by measuring a pulse from a photocell affixed to the back of the screen and illuminated by a small square on the corner of the same video frame as the appearance of any new stimulus. The monkey could not see the photocell or its illumination square. Monkeys were trained to sit in a primate chair with their head fixed and perform the two tasks used in this experiment. These tasks are described below.

#### Task 1: manual reaction time alone

The manual reaction time task consisted of two conditions that were randomly interleaved. In the first “without-distractor” condition, monkeys began the task by grabbing hold of a metal bar that triggered the presentation of a central white fixation point (Fig. 1a). The monkeys had to maintain fixation throughout the trial, until they were asked to initiate the memory-guided saccade. After a delay of up to 1,700 ms, a white spot (the “target”; Fig. 1b) was flashed for 50 ms at one of four randomly chosen locations at 12° eccentricity with one location in each quadrant; the four locations were changed at the beginning of each session. The monkeys had to remember this target location (the “saccade goal”) because they were required to make a saccade to this location at the end of the trial. After a second delay of 1,000, 1,300, 1,600, or 1,800 ms (chosen randomly for each trial) following the target flash, a static Gabor patch (the “probe” Fig. 1d) was flashed with equal probability either at or opposite the saccade goal on 67% of trials. The monkey then had 600 ms to remove its hand from the bar. If the monkey did this, then the fixation point was extinguished 800 ms after the probe appearance (Fig. 1e) signaling that the monkey should make the planned saccade. If the monkey made the appropriate saccade within 300 ms, it was rewarded with a drop of water. On the remaining 33% of trials, instead of presenting a probe, the fixation point was turned off. The monkey had to make the memory-guided saccade within 300 ms while continuing to hold the bar to receive the reward. These trials served as catch trials that successfully discouraged the monkey from guessing and releasing the bar prematurely before the probe appeared (see Results).

The second, “with-distractor” condition was identical to the without-distractor condition, except that a



**Fig. 1** Schematic diagram of the main task. The monkey initiated the task by grasping a bar and fixating a central spot (a). A target spot flashed for 50 ms at one of four locations indicating the goal of the future saccade (b). On some trials, after 600 ms, a distractor flashed at or opposite the saccade goal (c). Almost 700–1,800 ms after the target flash, a Gabor probe was flashed on 75% of trials at or opposite the saccade goal for 575 ms (d). The monkey had to

release the bar within 600 ms of probe appearance. About 800 ms after the probe appeared, the fixation point went off, and within 300 ms, the monkey's eye had to reach and remain within a region around the saccade goal (boundaries indicated by *black box* on figure; black box not visible on screen during the experiment) (e). For more details, see [Methods](#)

task-irrelevant distractor was flashed 600 ms after the saccade target (Fig. 1c), i.e. between the presentations of the target and probe. The distractor appeared with equal probability either at or opposite the saccade goal. The distractor was not informative about any aspect of the task. In addition, in the “with-distractor” condition, 20% of trials were catch trials. Finally, in the “with-distractor” condition, the delay between target flash and probe appearance was chosen randomly on each trial from a discrete set of nine different times from 700 to 1,800 ms. With-distractor and without-distractor conditions were randomly interleaved; the with-distractor condition was used for 62.5% of trials.

In all conditions, the target and distractor were small spots of  $0.35^\circ$  diameter and 47% contrast. The probe was always a static Gabor patch with a contrast of 87%, spatial frequency of 1.8 cycles/deg, Gaussian standard deviation of  $1.5^\circ$  and a visible radius of about  $2^\circ$ . During the task the monkey's point of gaze had to remain within  $5.5^\circ$  of the fixation point until fixation point disappearance, after which the monkey had 300 ms to move its gaze to within  $5.5^\circ$  of the saccade goal. If the animals successfully reached the window around the saccade goal, the saccade target was re-illuminated 350 ms

following the disappearance of the fixation point. Post-hoc analysis showed that monkey W rarely went more than  $3.2^\circ$  away from the fixation point and monkey I rarely went more than  $1.8^\circ$  away from the fixation point. If the monkey's eye left the fixation window prior to the appearance of the probe, the trial was aborted and repeated. If the monkey did not release the bar within 600 ms of the probe presentation, the trial terminated without reward, the screen flashed briefly, and the appearance of the next trial was delayed (a “time-out”). The monkey was also given a screen-flash and a time-out if he did not make the appropriate memory-guided saccade or released the bar prematurely.

#### Task 2: interleaved discrimination/reaction time

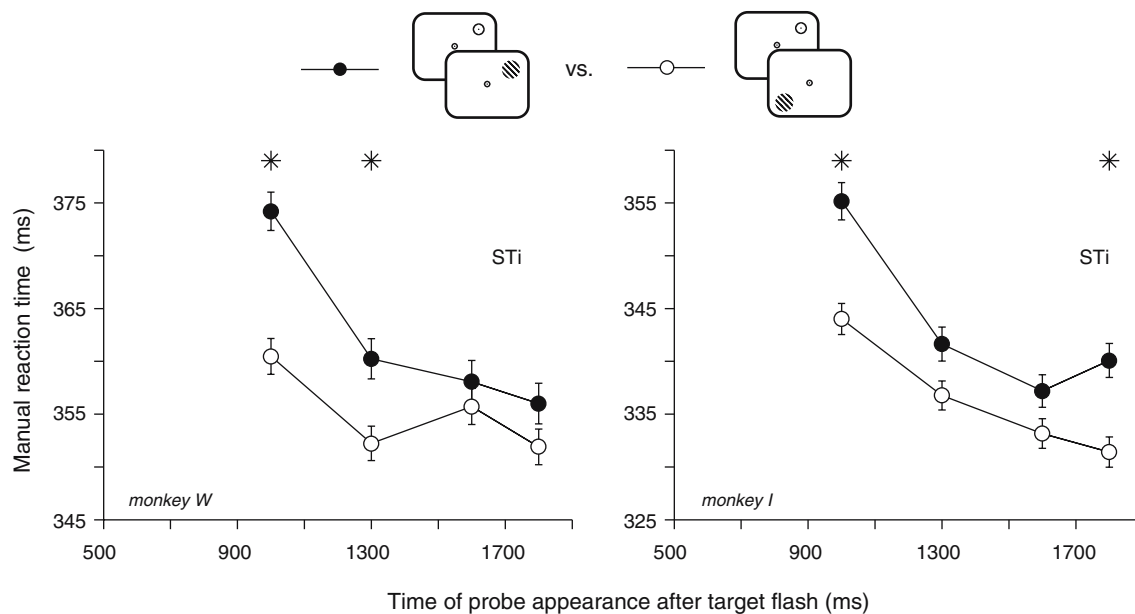
Monkey I had previously learned a task in which the probe, instead of being a signal to release its hand from the bar, was a go/nogo signal that determined whether or not the monkey had to make the planned saccade (Bisley and Goldberg 2003). The interleaved task, used only in monkey I, consisted of two kinds of tasks presented in an interleaved manner. In half of the trials, the

monkey performed a modified version of Task 1 in which there were no catch trials and a distractor appeared on 80% of trials. Of those 80% of trials the distractor appeared at the saccade goal 90% of the time. Also in this version of the task, the saccade target could lie anywhere along a circle at  $12^\circ$  eccentricity, rather than be chosen from four discrete locations as in Task 1 and the probe appeared either 400 or 600 ms after the distractor or, if there was no distractor, 1,200 ms after the saccade target. On the remaining half of the trials, the monkey performed the go/nogo discrimination task. The initial part of the task was similar to the one described above: the monkey initiated a trial by placing its hand on the bar, after which a fixation point appeared that the monkey had to fixate. After an interval of fixation the target appeared for 50 ms at a random location along a circle with a radius of  $12^\circ$ . In 80% of the trials, the distractor was flashed for 50 ms either at the saccade goal (90% of the time) or in the opposite quadrant at the same eccentricity. However, instead of the bar-release probe appearing, a go-nogo probe appeared for one or two video frames (17 or 35 ms), 1,000 or 1,200 ms after the target had appeared. The go-nogo probe consisted of a Landolt ring ( $1.5^\circ$  diameter,  $0.15^\circ$  thick, 2–12.5% contrast, with a  $0.5^\circ$  gap on either side) and could appear at or opposite the saccade goal with equal probability. The Landolt ring was accompanied by three complete rings of the same size and brightness that

appeared at the corresponding locations in the other three quadrants. The monkey's task was to indicate the side of the probe that the gap was on by either making the planned saccade (a "go" trial; the correct response for a probe with the gap on the left) or maintaining fixation once the fixation spot was extinguished (a "nogo" trial; the correct response for a probe with the gap on the right). The monkey received a drop of water as reward for correctly making or withholding the saccade depending upon the orientation of the probe.

#### Data analysis

All data analysis was performed using MATLAB (The Mathworks Inc., Natick, MA). Manual reaction times across all sessions for each condition from a given monkey were pooled together before comparison; we verified that performing comparisons on a session-by-session basis and then averaging the comparisons did not change the results presented here. Manual reaction times less than 200 ms were discarded as being pre-emptive. They represented about 0.6% of correct trials in monkey W and about 0.9% of correct trials in monkey I, and their omission does not make any material difference to the results presented here. In general, we have adopted the method of comparing manual reaction times following probes presented at different delays after



**Fig. 2** Effect of the saccade goal on manual reaction times in trials where no distractor was presented. *Ordinate* mean manual reaction times, *Abscissa* time after flash of saccade target, *Filled circles* probe at saccade goal, *Open circles* probe opposite the saccade goal. Data from monkey W in the left column, and from monkey I in the right column. *Asterisks* indicate that filled and open circles at that time were significantly different from each other (*t* test on transformed data,  $P < 0.05$ , Bonferroni correction applied, see

**Methods**). The characters *S*, *T*, and *I* represent the two factors (*S* for stimulus condition, and *T* for time after saccade target flash) and their interaction (*I*) in the ANOVA; *capital letters* indicate that the term was significant at the  $P < 0.01$  level (*F* test for significance). All *error bars* show standard error of the mean. *Cartoons* at the top of the figure summarize the stimulus conditions corresponding to open and filled circles

the target during two different stimulus conditions (e.g., probe at saccade goal vs. probe opposite saccade goal). To perform the comparison, we used a two-factor analysis-of-variance (ANOVA) with the stimulus condition (S) and time between target flash and probe presentation (T) as the explanatory factors. Since the variance of the manual reaction times was found to increase linearly with the mean, we first transformed the manual reaction times by taking the reciprocal before performing the ANOVA; this transformation made the variances more similar across conditions. All results significant at the 0.01 level ( $F$  tests; type III sums of squares) are presented in Results; when a term is not mentioned, it is because it was not found to be significant. In addition, at each given delay, we also performed a pairwise comparison using a two-sample  $t$  test to identify the delays that contributed to the stimulus-condition effects in the ANOVA. All pairwise comparisons were made at the 0.05 level using Bonferroni-corrected significance levels; we used the number of delays at which the comparisons were being made to make the correction. For example, in Fig. 2 the correction was made for nine simultaneous comparisons. In the manual reaction time task, there were six equiprobable stimulus conditions where a bar-release was required depending on location of saccade goal and presence/location of distractor. On average, there were 1,396 trials per stimulus condition for monkey W and 3,345 trials per stimulus condition for monkey I. Ns for the interleaved task are given in the legend to Fig. 5.

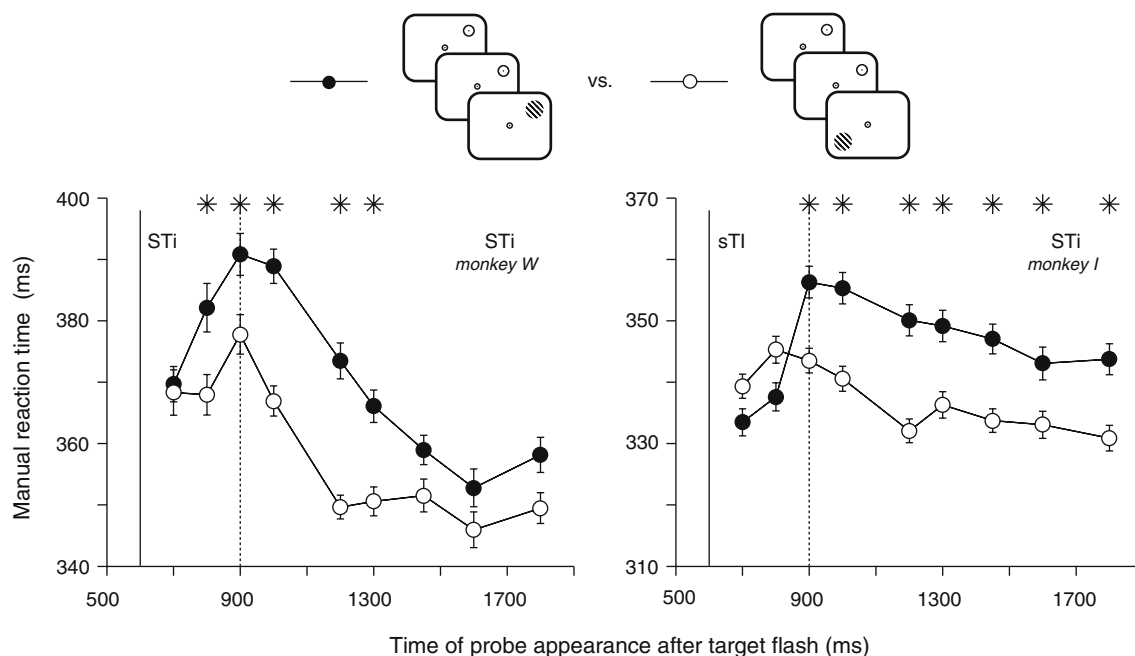
## Results

### Manual reaction times at the goal of a memory guided saccade

In order to examine the effect of planning a memory-guided saccade on manual reaction times, we compared the manual reaction times to probes presented during the delay period at and opposite the goal of a planned memory-guided saccade in trials where no distractor was presented. Manual reaction times were consistently longer when the probe appeared at the saccade goal (Fig. 2; filled circles) than when it appeared opposite the saccade goal (Fig. 2; open circles). ANOVA revealed strongly significant main effects of stimulus condition (S) for both monkeys [ $F(1,2913)=25.8$ ,  $P\sim 10^{-7}$  for monkey W and  $F(1,6738)=33.61$ ,  $P\sim 10^{-8}$  for monkey I]. The time-interval between target and probe onset (T) also strongly affected manual reaction time for both monkeys [ $F(3,2913)=22.5$ ,  $P < 10^{-12}$  for monkey W,  $F(3,6738)=38.45$ ,  $P < 10^{-12}$  for monkey I].

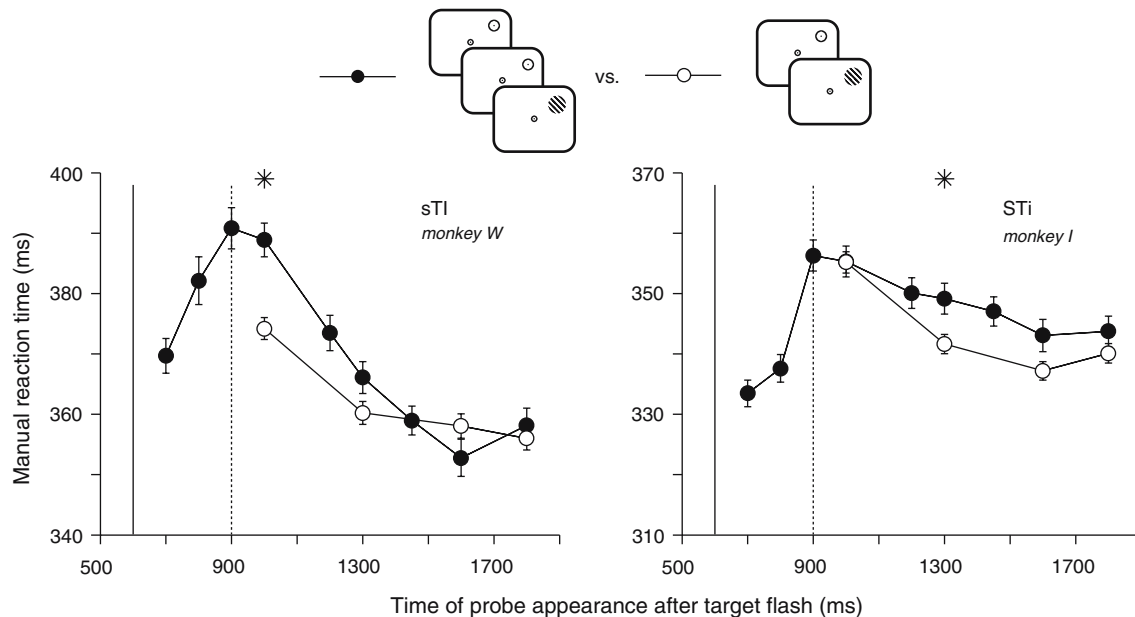
### Effects of a distractor at the saccade goal on the manual reaction-time disadvantage at the saccade goal

Distractors flashed at the probe site exert a biphasic effect on reaction time, initially facilitating it and subsequently prolonging it (Posner et al. 1985). To see if



**Fig. 3** Effect of the saccade goal on manual reaction times when a distractor was flashed at the saccade goal 600 ms after the saccade target flash. *Ordinate* mean manual reaction times, *Abscissa* time after flash of saccade target, *Filled circles* probe at saccade goal, *Open circles* probe opposite the saccade goal. *Solid vertical line*

indicates the time at which distractor was flashed. *Dotted line* at 900 ms demarcates the early (0–300 ms after distractor flash) and late (300–1,800 ms after distractor flash) phases; the ANOVA was performed separately for the early and late phases. All other conventions as in Fig. 2



**Fig. 4** Effect of the distractor on manual reaction times when the probe was at the saccade goal. *Ordinate* mean manual reaction times, *Abscissa* time after flash of saccade target, *Filled circles* a

distractor was flashed at the saccade goal, *Open circles* no distractor was flashed. All other conventions as in Fig. 2

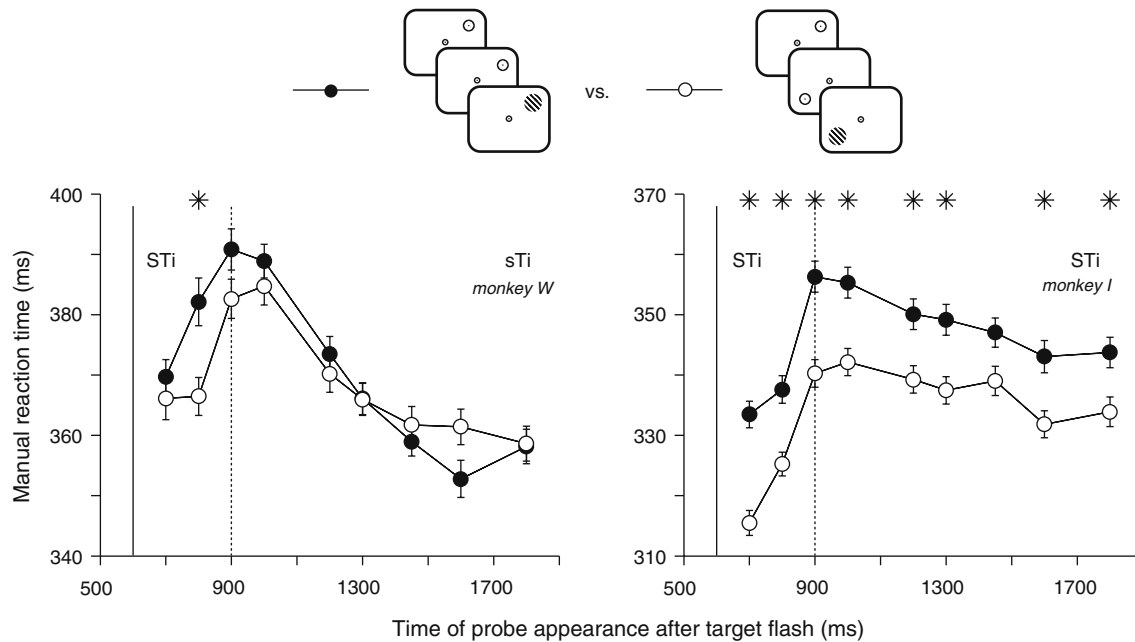
flashed distractors had a similar effect on the interaction between saccade plans and manual reaction time, we examined the effects of a distractor presented at the saccade goal between target flash and probe presentation on the manual reaction time disadvantage at the saccade goal. We found that a distractor flashed at the saccade goal had a biphasic effect. It initially eliminated the manual reaction-time disadvantage at the saccade goal, but subsequently increased the disadvantage even more (Fig. 3). Similar biphasic effects of flashed stimuli on manual reaction times following subsequent probes at the same location have been reported frequently (Klein 2000). In order to study these two phases separately, we divided the manual reaction times into those from responses to probes appearing within 300 ms of the distractor, and those from responses to probes appearing 300–1,800 ms after the distractor. We refer to these intervals as early and late phases, respectively. In trials without a distractor, all manual reaction times were categorized as late phase manual reaction times.

When both the distractor and the probe appeared at the saccade goal, late phase manual reaction times in both monkeys were longer compared to when the probe was opposite the saccade goal [Fig. 3; S factor for late phase,  $F(1,2183)=84.6$ ,  $P<10^{-12}$  for monkey W,  $F(1,5229)=99.12$ ,  $P<10^{-12}$  for monkey I]. Starting from their peak value at about 300 ms, late phase manual reaction times decreased with time for both conditions [ $F(6,2183)=42.66$ ,  $P<10^{-12}$  for monkey W and  $F(6,5229)=10.04$ ,  $P\sim 10^{-11}$  for monkey I]. The difference between the late phase manual reaction times in the two conditions did not change significantly with time; however, this change with time was of

borderline significance in monkey W [late-phase interaction term:  $F(6,2183)=2.65$ ,  $P\sim 0.014$  for monkey W and  $F(6,5229)=0.43$ ,  $P\sim 0.857$  for monkey I].

In the early phase, both monkeys showed an increase in manual reaction times following distractor onset. This was statistically significant in both monkeys [early phase T factor:  $F(2,918)=9.36$ ,  $P\sim 10^{-4}$  for monkey W and  $F(2,2328)=19.95$ ,  $P\sim 10^{-9}$  for monkey I]. Monkey I initially showed slightly shorter manual reaction times at the saccade goal for the earliest delays. By 300 ms after distractor presentation, the manual reaction times at the saccade goal became longer. This led to a statistically significant interaction term during the early phase [ $F(2,2328)=12.8$ ,  $P\sim 10^{-6}$ ]. In monkey W, the manual reaction times were already similar by 100 ms after distractor presentation and were significantly longer at 200 ms after distractor onset; consistent with this, the stimulus-condition factor was statistically significant for the early phase [ $F(1,918)=12.1$ ,  $P\sim 0.0005$ ; the interaction term was not significant,  $F(2,918)=1.28$ ,  $P\sim 0.28$ ].

Flashing the distractor at the saccade goal appeared to slow down reaction times at the saccade goal even further: late phase manual reaction times were increased following a probe at the saccade goal (Fig. 4; filled circles) compared to trials where no distractor was presented (Fig. 4; open circles). Although this effect varied between the two monkeys, the ANOVA indicated statistical significance for both monkeys; the effect of the distractor manifested itself in a statistically significant interaction term for monkey W and a statistically significant effect of stimulus condition for monkey I [S factor:  $F(1,2060)=5.57$ ,  $P\sim 0.02$ , interaction



**Fig. 5** Effect of the distractor on manual reaction times to a probe at the location of the distractor flash. *Ordinate* mean manual reaction times, *Abscissa* time after flash of saccade target, *Filled*

*circles* distractor flashed at the saccade goal, *Open circles* distractor flashed opposite the saccade goal. All other conventions as in Fig. 2

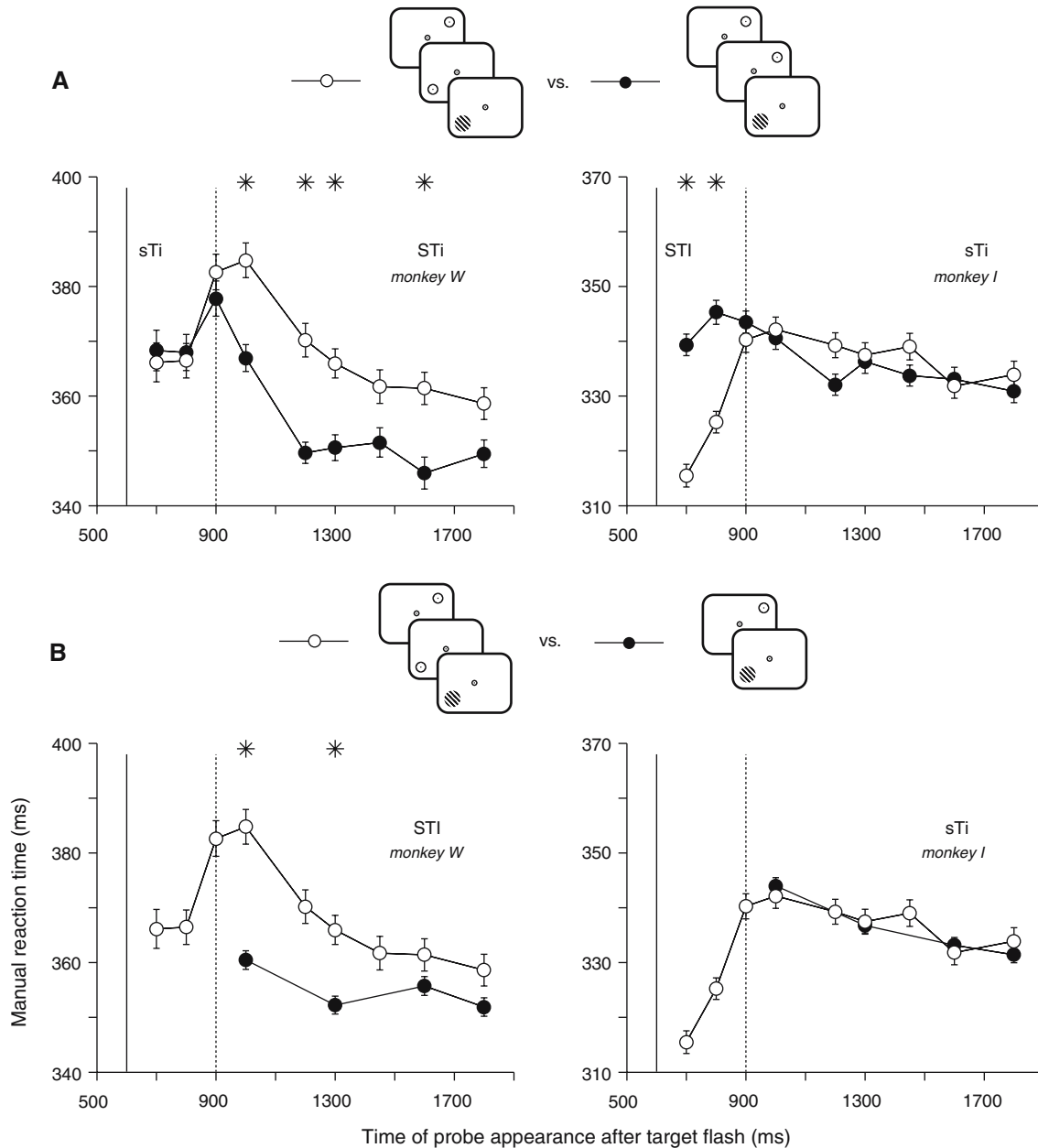
term:  $F(3,2060) = 5.77$ ,  $P \sim 10^{-3}$  for monkey W and S factor:  $F(1,4797) = 7.61$ ,  $P \sim 0.006$ , interaction term:  $F(3,4797) = 0.83$ ,  $P \sim 0.48$  for monkey I].

Finally, the biphasic effect of a distractor at the saccade goal was also apparent when we compared the manual reaction times to a probe at the saccade goal in the condition where the distractor appeared at the saccade goal to the condition where the distractor appeared opposite the saccade goal. Manual reaction times to a probe at the saccade goal were faster after the distractor appeared at the saccade goal at the earliest times during the early phase (700 and 800 ms after target flash for monkey I and at 700 ms after target flash for monkey W;  $t$  test,  $P < 0.05$ ). Subsequently, during the late phase, manual reaction times to a probe at the saccade goal were consistently slower if the distractor appeared at the saccade goal [monkey I; S factor:  $F(1,5116) = 79.73$ ,  $P < 10^{-12}$ ; interaction term:  $F(6,5116) = 3.46$ ,  $P \sim 0.002$  and monkey W; S factor:  $F(1,2069) = 17.32$ ,  $P \sim 0.00003$ ; interaction term:  $F(6,2069) = 1.07$ ,  $P \sim 0.38$ ]. Manual reaction times were slower during the late phase by an average of 11.6 ms (SEM = 1.3 ms) for monkey I and by 6.3 ms (SEM = 1.7 ms) for monkey W if the distractor appeared at the saccade goal instead of opposite the saccade goal.

#### Effects of a flashed distractor on manual reaction times at the distractor location

Our prior results (Bisley and Goldberg 2003) indicate that a distractor flashed opposite the saccade goal transiently draws attention toward the distractor

location; attention then returns to the saccade goal after a delay. We were therefore interested in examining whether flashing a distractor led to a reduction of manual reaction times at that location. However, whereas the results thus far have been qualitatively similar for both monkeys, we found that the two monkeys showed different effects of distractor presentation on manual reaction times to probes presented at the distractor location. Presenting both the distractor and the probe at the same location (Fig. 5; open circles: opposite the saccade goal; closed circles: at the saccade goal) caused a rapid increase in early phase manual reaction times peaking at 300 ms after the distractor flash [early phase T factor:  $F(2,888) = 16.43$ ,  $P \sim 10^{-7}$  for monkey W and  $F(2,2215) = 63.29$ ,  $P < 10^{-12}$  for monkey I]. In the late phase, manual reaction times steadily decreased in both conditions [late phase T factor:  $F(6,2068) = 35.94$ ,  $P < 10^{-12}$  for monkey W and  $F(6,4961) = 7.11$ ,  $P \sim 10^{-7}$  for monkey I]. Consistent with the slowing-down of manual reaction times at the saccade goal described earlier, early phase manual reaction times at the saccade goal were slower for both monkeys [S factor in ANOVA, Monkey W:  $F(1,888) = 10.71$ ,  $P \sim 10^{-3}$ ; Monkey I:  $F(2,2215) = 70.4$ ,  $P < 10^{-12}$ ]. In the late phase, only Monkey I showed slower manual reaction times at the saccade goal [ $F(1,4961) = 68.55$ ,  $P < 10^{-12}$ ]. In monkey W, manual reaction times slowed down in the late phase at the distractor site when the distractor was flashed opposite the saccade goal; this slowing down was sufficient to make the manual reaction time opposite the saccade goal not different from manual reaction time at the saccade goal [S factor for late phase:  $F(1,2068) = 0.07$ ,  $P \sim 0.8$ ].



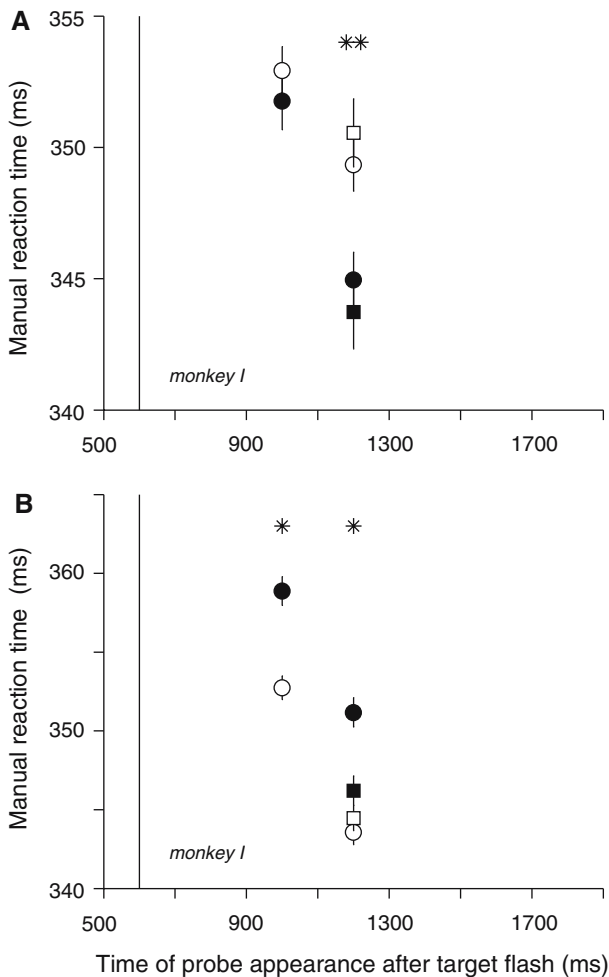
**Fig. 6** Effect of the distractor flashed opposite the saccade goal on manual reaction times to a probe opposite the saccade goal. Ordinate mean manual reaction times, Abscissa, time after flash of

saccade target, *Open circles* distractor flashed opposite the saccade goal. All other conventions as in Fig. 2. **a** *Filled circles* distractor flashed at the saccade goal. **b** *Filled circles* no distractor flashed

The pattern of increase in early phase manual reaction times suggests that the distractor led to faster manual reaction times at its spatial location (facilitation) and that this facilitation decayed within about 300 ms, the time at which manual reaction times following distractor flash were longest. However, when we tested this possibility we found evidence for facilitation only in monkey I (Fig. 6). This was done by comparing early phase manual reaction times following probes opposite the saccade goal when the distractor was flashed either in the same (Fig. 6a; open circles) or opposite location (Fig. 6a; filled circles). For this monkey, early phase

manual reaction times opposite the saccade goal were initially faster when a distractor was flashed there [S factor for early phase:  $F(1,2251) = 100.21$ ,  $P < 10^{-12}$ ] and then increased until the end of the early phase [T factor for early phase:  $F(2,2251) = 28.87$ ,  $P < 10^{-12}$ ; interaction term:  $F(2,2251) = 16.48$ ,  $P \sim 10^{-7}$ ] so that by the beginning of the late phase, the manual reaction times from the two conditions were not statistically different [S factor for late phase:  $F(1,5086) = 1.43$ ,  $P \sim 0.23$ ; interaction term:  $F(6,5086) = 1.23$ ,  $P \sim 0.29$ ]. On the contrary, monkey W's early phase manual reaction times were not statistically different in the two

conditions [S factor for early phase:  $F(1,952)=0.1$ ,  $P\sim 0.75$ , interaction:  $F(2,952)=0.81$ ,  $P\sim 0.44$ ]; in the late-phase, manual reaction times opposite the saccade goal were actually longer when the distractor was at the probe location [S factor for late phase:  $F(1,2145)=77.08$ ,  $P < 10^{-12}$ ]. Thus, monkey I appeared to show early phase facilitation, but no late phase inhibition, while monkey W showed no early phase facilitation, but strong late phase inhibition. We note that the lack of transient facilitation at the distractor location in monkey W was also seen when the distractor was presented at the saccade goal (Fig. 3); monkey I, however, again showed a transient facilitation at the distractor location in that case as well.



**Fig. 7** Effect of the saccade goal on manual reaction times under interleaved task conditions. *Ordinate* mean manual reaction times, *Abscissa* time after flash of saccade target, *Filled symbols* probe at the saccade goal, *Open symbols*: probe opposite the saccade goal, *Circles* a distractor was flashed at the saccade goal (1,251 trials in **a** and 2,081 trials in **b**, per data point on average). *Squares* no distractor was flashed (718 trials in **a** and 1,825 trials in **b**, per data point on average). *Asterisks* indicate results of pairwise *t* tests on filled and open symbols. All other conventions as in Fig. 2. **a** Manual reaction time trials interleaved with trials in which the monkey performed a discrimination task. **b** Manual reaction times performed without any other interleaved task

The slower late phase manual reaction times following probes opposite the saccade goal in monkey W were likely due to the presence of a distractor opposite the saccade goal, rather than being an effect of the distractor at the saccade goal. This is because for monkey W late phase manual reaction times were slower when both the distractor and the probe were flashed away from the saccade goal (Fig. 6b; open circles), as compared to trials in which no distractor was ever flashed and the probe appeared away from the saccade goal (Fig. 6b; closed circles) [S factor for late phase:  $F(1,2070)=54.41$ ,  $P < 10^{-12}$ ]. This late phase manual reaction time difference in monkey W appeared to diminish with time [interaction term for late phase:  $F(3,2070)=5.61$ ,  $P\sim 10^{-3}$ ]. However, in monkey I, the late phase manual reaction times were not statistically different under the two conditions [S factor for late phase:  $F(1,4773)=0.11$ ,  $P\sim 0.74$ ; interaction:  $F(3,4773)=0.45$ ,  $P\sim 0.72$ ].

#### Effects of time during the late phase

There was a consistent effect on late phase manual reaction times as the delay between target and probe presentation increased. As noted above, both monkeys showed a systematic decrease in late phase manual reaction times under all stimulus conditions (time term factor for late phase,  $P < 10^{-9}$  for 8 of the 12 stimulus conditions across both monkeys,  $P < 10^{-5}$  for 1 condition, and  $P < 10^{-2}$  for the remaining 3 stimulus conditions). This gradual manual reaction time decrease is likely to be due to the commonly noted effects of increasing instantaneous probability of probe appearance as the trial progressed (for a review, see Niemi and Naatanen 1981; Janssen and Shadlen 2005). To establish whether this late phase manual reaction time decrease was due to a speed-accuracy trade off, we examined trials in which the animals incorrectly released the bar prior to the appearance of the probe. We found that these errors accounted for approximately 1–5% of all trials, and almost all these errors were due to the monkeys releasing the bar to the onset of the distractor. Other than these responses, neither monkey pre-released in more than a few dozen trials (out of tens of thousands) and so there was not enough data to compare the percentage of pre-release errors with correct manual reaction times at different delays. The late phase manual reaction time decrease is therefore unlikely to be the result of a speed-accuracy tradeoff.

#### Manual reaction times in the interleaved task paradigm

The unexpected increase in late phase manual reaction times following probes at the saccade goal combined with prior findings of a perceptual advantage at the saccade goal in the discrimination task (Bisley and Goldberg 2003) raises the possibility that the slower manual reaction times at the saccade goal may arise

from putative post-perceptual stages that influence manual reaction time but not discrimination ability. Alternatively, the attentional processes that improve contrast sensitivity at the saccade goal could be different from the attentional processes that speed manual reaction time. However, this speculation rests upon a combination of data from two different studies; there is no direct evidence that a perceptual advantage exists at the saccade goal in the current manual reaction time task. Though one of the monkeys in the manual reaction time task discussed here (monkey I) was also a part of the earlier study and was therefore known to show a perceptual advantage at the goal of the saccade in the previous task, it is still possible that this monkey may have changed his strategy for the manual reaction time task. We therefore trained monkey I to perform a dual task, incorporating both the discrimination task (Bisley and Goldberg 2003) and the manual reaction time task concurrently: the two types of trials were performed in an interleaved manner. The monkey did not know if the trial would be a manual reaction time trial or a go/no-go discrimination trial until the probe appeared. It was only when the probe appeared that he knew the nature of the task he had to perform on that trial, depending on whether the probe was a Gabor patch or a Landolt ring. We were particularly curious to see if we could demonstrate that the slowed late phase manual reaction times at the saccade goal coexisted with a perceptual advantage at the same location. However, we instead found that when monkey I performed the manual reaction time task along with the perceptual discrimination task, late phase manual reaction times became faster at the saccade goal (Fig. 7a; filled symbols) compared to late phase manual reaction times opposite the saccade goal (Fig. 7a; open symbols). 1,200 ms after the target appeared, manual reaction times were significantly faster at the saccade goal both in trials in which a distractor was presented at the saccade goal [circles;  $t(6,959)=3.6$ ,  $P\sim 0.0003$ ] and in trials in which no distractor was presented [squares;  $t(6,959)=4.23$ ,  $P\sim 0.00002$ ]. A non-significant trend was found 1,000 ms after the target appeared when a distractor was flashed at the saccade goal [circles;  $t(6,959)=1.78$ ,  $P\sim 0.075$ ].

Since we found faster manual reaction times at the saccade goal in the interleaved task, it is clear that the effects on manual reaction time at the saccade goal were task-dependent. However, some task parameters for the manual reaction time component of this interleaved task were different from the pure manual reaction time task (see [Methods](#) for differences). So we repeated the experiment by running a pure manual reaction time task again, but with the same task parameters as the manual reaction time component of the interleaved task (Fig. 7b). Now manual reaction times reverted to being slower at the saccade goal (note reversal of open and filled circles in Figs. 7a, b); this effect was statistically significant in trials in

which a distractor was presented at the saccade goal [circles;  $t(12,873)=-3.94$ ,  $P\sim 10^{-4}$  at 1,000 ms and  $t(12,873)=-5.5$ ,  $P\sim 10^{-8}$  at 1,200 ms].

In parallel with the shorter manual reaction times at the saccade goal in the interleaved task, the monkey's performance on the perceptual discrimination task was better at the saccade goal. Even though we used a suprathreshold go/nogo probe, the monkey was significantly more accurate when the probe was at the saccade goal than opposite the saccade goal when no distractor was flashed (82% vs. 75% correct;  $P\sim 0.048$ , chi-squared test) and at the shorter delay when the distractor was flashed at the target location (82% vs. 76% correct;  $P\sim 0.029$ ), though not at the longer delay ( $P\sim 0.72$ ). Thus, the results suggest that there was a perceptual advantage at the goal of the saccade, consistent with the manual reaction times measured in the interleaved task (Fig. 7a) and with previous results from a more complete study (Bisley and Goldberg 2003).

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## Discussion

Monkeys demonstrate an attentional advantage at the goal of a planned memory guided-saccade, as measured by a lower contrast threshold (Bisley and Goldberg 2003). Similar attentional advantages at the locations of planned saccades have been demonstrated in humans (Van der Stigchel and Theeuwes 2005). Faster manual reaction times following the appearance of a suprathreshold visual stimulus have also been frequently used as a measure of visual attention. In this study, we found that despite this previously demonstrated attentional advantage at the saccade goal, manual reaction times on a detection task were actually slower when the probe appeared at the saccade goal; we have documented the magnitude and time-course of this effect in detail. A similar result has been obtained recently for humans 1,500 ms into the delay of a memory-guided saccade task (Ostendorf et al. 2004). We then attempted to demonstrate explicitly that slower manual reaction times coexisted with lower contrast thresholds at the saccade goal by interleaving the detection and perceptual discrimination tasks. However, we found that manual reaction times were then faster at the saccade goal.

The most plausible explanation for our findings is that an inhibitory process which slowed down manual reaction times was evoked at the saccade goal by the appearance of the memory-guided saccade target and that this process was overshadowed due to increased task difficulty during the interleaved task. This putative inhibitory process is probably identical to the process(es) involved in the phenomenon called inhibition-of-return, where manual reaction times are slower in response to probes presented at previously cued locations (Posner et al. 1985; Klein 2000). The inhibitory effect could be a result of a selective attentional deficit at the saccade goal, a sensorimotor or motor inhibition that delayed responses to visual stimuli appearing at the saccade goal,

or a motor inhibition that resulted from the necessity of suppressing the natural tendency to make a saccade toward the flashed target during the delay period of the memory-guided saccade. All three mechanisms have been invoked to explain inhibition-of-return as well (Chelazzi et al. 1995; Taylor and Klein 2000; Coward et al. 2004; Klein 2004).

The reversal of the slowing down of manual reaction times in the interleaved task reiterates the importance of task conditions in interpreting the results of behavioral measurements. At the beginning of each trial in the interleaved task, the monkey did not know if the trial would be a simple suprathreshold detection task or a difficult discrimination task. Presumably, the monkey changed its strategy to be able to perform the discrimination task. We suggest that this strategy change involved a greater engagement of endogenous attention. The linkage between spatial working memory and attention (Awh and Jonides 2001) as well as the linkage between oculomotor preparation and visuospatial attention (Rizzolatti et al. 1994) predict that endogenous attention should be stronger at the saccade goal. Because the interleaved task is much more attentionally demanding than the detection task, the greater engagement of attentional resources may amplify the sustained attentional advantage at the saccade goal. As a result of this amplification, the endogenous attentional advantage at the saccade goal could successfully override the exogenously evoked inhibitory process at the saccade goal to produce speeded manual reaction times at that location. This suggestion is supported by several recent studies (Berger and Henik 2000; Berlucchi et al. 2000; Fecteau et al. 2004; Lupianez et al. 2004) that show that increasing endogenous attention to the cued location by increasing cue validity decreases the expression of inhibition-of-return. Along similar lines, it has been suggested that inhibition-of-return emerges later in discrimination tasks than in detection tasks as a result of the increased engagement of attentional resources due to increased perceptual demands (Klein 2000; Lupianez et al. 2001).

In addition, we found that a distractor flashed away from the saccade goal evoked only early facilitation in monkey I, and only late inhibition in monkey W. Because monkey I had much more experience than monkey W with psychophysical tasks like those in this paper, he may have been performing the task under lesser perceptual load and therefore been less able to filter out the distractor (Lavie 2005). But while this explains why monkey W fails to show facilitation due to the distractor, it does not explain why Monkey I does not show "inhibition" even at long delays when attention has presumably left the distractor site. The variability in the expression of inhibition is not easily explicable in terms of known phenomena in the literature.

There is a potential physiological correlate for the slowed manual reaction times following a probe at the saccade goal. Several studies have now reported that in the salience maps of the parietal cortex and superior

colliculus, a stimulus presented at a cued location evokes lower activity than a stimulus presented at a location other than the cued location (Steinmetz et al. 1994; Robinson et al. 1995; Robinson and Kertzman 1995; Steinmetz and Constantinidis 1995; Powell and Goldberg 2000; Constantinidis and Steinmetz 2001; Dorris et al. 2002; Bell et al. 2004; Bisley et al. 2004; Fecteau et al. 2004). Motor responses to the probe in simple detection tasks may be plausibly expected to be driven by the activity following probe presentation, and Munoz and colleagues (Dorris et al. 2002; Bell et al. 2004; Fecteau et al. 2004) have demonstrated clearly that the smaller responses in the superior colliculus following probe presentation at cued locations are accompanied by longer saccadic latencies to the probe presented at cued locations (inhibition-of-return); this was true for both valid and invalid cues. Therefore, in our task, the smaller responses to the probe presented at the saccade goal would lead to slower manual reaction times following probe presentation at the saccade goal. Interestingly, this explanation predicts that during the interleaved task, responses to the probe in the salience maps of the parietal cortex (or superior colliculus) that subserved performance on manual bar-release tasks should be higher when the probe is presented at the saccade goal, thereby leading to faster manual reaction times following probe presentation at the saccade goal. The existing data support this prediction. In the studies that found that the responses to the probe were lower at the attended locations, the monkeys were performing easy tasks that either did not require them to pay much attention to the probe [suprathreshold detection tasks with either manual (Robinson et al. 1995; Robinson and Kertzman 1995) or saccadic (Dorris et al. 2002; Bell et al. 2004; Fecteau et al. 2004) responses, or location matching tasks (Steinmetz et al. 1994; Steinmetz and Constantinidis 1995; Constantinidis and Steinmetz 2001)] or actually allowed them to ignore the stimulus altogether (Powell and Goldberg 2000; Bisley et al. 2004). However, in a recent study where monkeys were performing a difficult discrimination task on the probe, thus engaging attentional resources effectively and also requiring them to pay attention to the probe, the response to the probe was higher in visual and visuomotor cells of the superior colliculus when the probe was presented at the attended location (Ignashchenkova et al. 2004). Activity in visual cells after probe onset (600 ms following cue presentation) was higher when the probe was presented at the attended location with both exogenous and symbolic cueing. Activity in visuomotor cells was similarly higher at the attended location after exogenous cueing; the increase with symbolic cueing was suggestive, but not statistically significant. Similarly in another study, engaging endogenous attention at the cued location by using valid cues resulted in both larger responses to the probe and shorter saccadic reaction times following probe presentation at the cued location

(Fecteau et al. 2004). The physiological data, combined with our results, therefore suggest that the attentional requirements of the task performed determines whether reaction times following probe presentation are slower or faster, and neural responses to the probe smaller or larger, when the probe is presented at the cued location.

A measured change in reaction time as a result of an experimental manipulation can result from underlying effects on sensory, sensorimotor, and/or motor processing stages. Attempts to resolve the locus responsible for a change in reaction time have led to an active and enduring controversy in the literature on inhibition-of-return about the role of attentional deficits in creating slower reaction times to probes at recently cued locations (Taylor and Klein 2000). To determine whether attention was allocated to the goal of a planned saccade, Bisley and Goldberg (2003) used a discrimination task and showed that contrast thresholds were lower at the saccade goal; this provided a direct demonstration of endogenous attentional allocation to the saccade goal. This allocation of endogenous attention was accompanied by increased activity immediately prior to probe presentation in the region of parietal cortex representing the attended location. Hypotheses developed in the inhibition-of-return literature indicate that the slower manual reaction times following probe presentation at the saccade goal during the detection task could be the result of either a deficit in attentional orienting toward the probe following probe onset or the result of a slowing down of visuomotor or motor processes mediating the response to a probe at the saccade goal (e.g., Taylor and Klein 2000). In principle, both these effects could be mediated by a suppressed response following probe presentation at the saccade goal in the salience maps that subserve performance on manual bar-release tasks. In any case, the greater engagement of endogenous attentional resources during the interleaved task could maintain attention at the saccade goal and override the inhibitory effects that underlie the emergence of slowed reaction times at the saccade goal during the detection task. We suggest that this would be accompanied by an increased response in these same salience maps to probe onset at the saccade goal under these conditions. Future physiological studies that examine these predictions under different task conditions will help resolve the relationship between the neural responses in salience maps and measures of attention and performance.

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## References

- Awh E, Jonides J (2001) Overlapping mechanisms of attention and spatial working memory. *Trends Cogn Sci* 5:119–126
- Bell AH, Fecteau JH, Munoz DP (2004) Using auditory and visual stimuli to investigate the behavioral and neuronal consequences of reflexive covert orienting. *J Neurophysiol* 91:2172–2184
- Berger A, Henik A (2000) The endogenous modulation of IOR is nasal-temporal asymmetric. *J Cogn Neurosci* 12:421–428
- Berlucchi G, Chelazzi L, Tassinari G (2000) Volitional covert orienting to a peripheral cue does not suppress cue-induced inhibition of return. *J Cogn Neurosci* 12:648–663
- Bisley JW, Goldberg ME (2003) Neuronal activity in the lateral intraparietal area and spatial attention. *Science* 299:81–86
- Bisley JW, Krishna BS, Goldberg ME (2004) A rapid and precise on-response in posterior parietal cortex. *J Neurosci* 24:1833–1838
- Chelazzi L, Biscaldi M, Corbetta M, Peru A, Tassinari G, Berlucchi G (1995) Oculomotor activity and visual spatial attention. *Behav Brain Res* 71:81–88
- Constantinidis C, Steinmetz MA (2001) Neuronal responses in area 7a to multiple stimulus displays: II. Responses are suppressed at the cued location. *Cereb Cortex* 11:592–597
- Coward RS, Poliakoff E, O’Boyle DJ, Lowe C (2004) The contribution of non-ocular response inhibition to visual inhibition of return. *Exp Brain Res* 155:124–128
- Deubel H, Schneider WX (1996) Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vision Res* 36:1827–1837
- Deubel H, Schneider WX (2003) Delayed saccades, but not delayed manual aiming movements, require visual attention shifts. *Ann N Y Acad Sci* 1004:289–296
- Dorris MC, Klein RM, Everling S, Munoz DP (2002) Contribution of the primate superior colliculus to inhibition of return. *J Cogn Neurosci* 14:1256–1263
- Fecteau JH, Bell AH, Munoz DP (2004) Neural correlates of the automatic and goal-driven biases in orienting spatial attention. *J Neurophysiol* 92:1728–1737
- Hays AV, Richmond BJ, Optican LM (1982) A UNIX-based multiple process system for real-time data acquisition and control. *WESCON Conf Proc* 2:1–10
- Hoffman JE, Subramaniam B (1995) The role of visual attention in saccadic eye movements. *Percept Psychophys* 57:787–795
- Ignashchenkova A, Dicke PW, Haarmeier T, Thier P (2004) Neuron-specific contribution of the superior colliculus to overt and covert shifts of attention. *Nat Neurosci* 7:56–64
- Janssen P, Shadlen MN (2005) A representation of the hazard rate of elapsed time in macaque area LIP. *Nat Neurosci* 8:234–241
- Judge SJ, Richmond BJ, Chu FC (1980) Implantation of magnetic search coils for measurement of eye position: an improved method. *Vision Res* 20:535–538
- Klein RM (2000) Inhibition of return. *Trends Cogn Sci* 4:138–147
- Klein RM (2004) Orienting and inhibition of return. In: Gazzaniga MS (ed) *The cognitive neurosciences*. MIT Press, Cambridge, pp 545–559
- Klein RM, Pontefract A (1994) Does oculomotor readiness mediate cognitive control of visual attention? Revisited! In: Umiltà C, Moscovitch M (eds) *Attention and performance XV*, vol XV, MIT Press, Cambridge, pp 333–350
- Kowler E, Anderson E, Doshier B, Blaser E (1995) The role of attention in the programming of saccades. *Vision Res* 35:1897–1916
- Lavie N (2005) Distracted and confused? Selective attention under load. *Trends Cogn Sci* 9:75–82

- Lupianez J, Milliken B, Solano C, Weaver B, Tipper SP (2001) On the strategic modulation of the time course of facilitation and inhibition of return. *Q J Exp Psychol A* 54:753–773
- Lupianez J, Decaix C, Sieroff E, Chokron S, Milliken B, Bartolomeo P (2004) Independent effects of endogenous and exogenous spatial cueing: inhibition of return at endogenously attended target locations. *Exp Brain Res* 159:447–457
- Niemi P, Naatanen R (1981) Foreperiod and simple reaction time. *Psychol Bull* 89:133–162
- Ostendorf F, Finke C, Ploner CJ (2004) Inhibition of visual discrimination during a memory-guided saccade task. *J Neurophysiol* 92:660–664
- Pestilli F, Carrasco M (2005) Attention enhances contrast sensitivity at cued and impairs it at uncued locations. *Vision Res* (in press)
- Posner MI, Rafal RD, Choate LS, Vaughan J (1985) Inhibition of return: neural basis and function. *Cog Neuropsychol* 2:211–228
- Powell KD, Goldberg ME (2000) Response of neurons in the lateral intraparietal area to a distractor flashed during the delay period of a memory-guided saccade. *J Neurophysiol* 84:301–310
- Rizzolatti G, Riggio L, Sheliga BM (1994) Space and selective attention. In: Umiltà C, Moscovitch M (eds) *Attention and performance XV*, vol XV, MIT Press, Cambridge, pp 231–265
- Robinson DL, Kertzman C (1995) Covert orienting of attention in macaques. III. Contributions of the superior colliculus. *J Neurophysiol* 74:713–721
- Robinson DL, Bowman EM, Kertzman C (1995) Covert orienting of attention in macaques. II. Contributions of parietal cortex. *J Neurophysiol* 74:698–712
- Sirotnin YB, Krishna SB, Bisley JW, Steenrod SC, Goldberg ME (2004) Manual reaction time during a memory-guided delayed saccade task [Abstract]. *J Vis* 4:446a
- Steinmetz MA, Constantinidis C (1995) Neurophysiological evidence for a role of posterior parietal cortex in redirecting visual attention. *Cereb Cortex* 5:448–456
- Steinmetz MA, Connor CE, Constantinidis C, McLaughlin JR (1994) Covert attention suppresses neuronal responses in area 7a of the posterior parietal cortex. *J Neurophysiol* 72:1020–1023
- Taylor TL, Klein RM (2000) Visual and motor effects in inhibition of return. *J Exp Psychol Hum Percept Perform* 26:1639–1656
- Van der Stigchel S, Theeuwes J (2005) The influence of attending to multiple locations on eye movements. *Vision Res* 45:1921–1927